Thermal management strategies for integrated hybrid vehicle subsystems

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Abstract

Intelligent thermal management is a key area of interest for delivering ever more efficient vehicles. The ability to redistribute and reroute thermal energy around the vehicle, it's subsystems and environment enables for example, quicker component conditioning to optimal operating conditions. This in turn can yield reduction in on-board energy source utilisation for things other than vehicle propulsion.

On BEVs (Battery Electric Vehicles) a particular area of interest is the thermal management of the battery and cabin, without requiring significant use of power from the battery itself. The interest in this area is to minimise the impact of subsystem conditioning on vehicle range.

Heat pumps are becoming more popular for transferring thermal energy throughout vehicle systems. Heat pump systems vary from simple ones which take heat out of the outside air, transferring it to vehicle subsystems which require heating up. Conversely the same heat pump system could be used for chilling the cabin air or other vehicle components that require cooling.

The coupling of vehicle subsystems to the heat pump heat exchangers requires careful design and evaluation of fluids routing throughout the vehicle. Conventional vehicle architectures may require substantial re-engineering to accommodate the heat pump fluid circuitry layout, particularly for heat pump systems which interact with multiple vehicle subsystems.

This paper applies systems engineering to the evaluation and selection of an integrated heat pump for BEV applications capable of transferring heat between several vehicle subsystems. Benefits of several control scenarios are evaluated to narrow down the feasible solutions prior to hardware development and demonstrator assembly. The scenarios cover both warm-up and pull-down situations with a particular focus on warm-up (predicted to be the worst case for BEV range reduction). The work identifies ways to minimise the use of PTC (Positive Thermal Coefficient) devices where electrical energy is used to heat up a fluid (cabin ventilation air, for example), such energy typically being drawn from the traction battery.

Benefits of the investigated heat pump configurations are given in terms of reduced heating power drawn from the traction battery but also improvement on vehicle range as a result of optimised thermal energy transfer across the vehicle systems.

1 Introduction

In vehicles, PTC heaters (Positive Thermal Coefficient) are used to heat up air (e.g. for warming up the cabin) where thermal energy from other sources (e.g. engine coolant system) is not sufficient or available.

PTCs require electrical energy to heat up the air passing through them. On BEVs, the absence of an internal combustion engine means that there is little waste heat generated which can be transferred to warm up the cabin and battery in cold weather conditions. PTCs have been used to heat up the cabin air and also the battery coolant in cold conditions to achieve optimal comfort and performance. The electric energy used by the PTCs comes from the vehicle battery, thus reducing the amount of electrical energy available to propel the vehicle along its duty cycle.
Although there might be lack of waste heat energy on BEVs in cold start conditions, heat could be extracted from subsystems which do not require heating and transferred to the ones that do.
The objective of this work is to find the configuration/control of heat pump and subsystem interactions that will yield the highest increase in range of a BEV (Battery Electric Vehicle) in a cold weather environment with respect to a baseline scenario where the cabin and battery are heated solely by means of PTC heaters. In summary we want to reduce the use of PTC heaters by transferring heat from other parts of the vehicle.

The practicalities of building prototypes to explore a series of heat pump configurations are complex and costly. In this project, CAE has been used to surmount the complexities and costs involved with real prototypes of system concepts and accelerate the feasibility studies of these systems. Several concepts are explored and the ones with the highest returns are selected for prototyping and practical testing.
No component specification has been selected prior to the CAE work other than sensible guidelines to parameters such as maximum heat exchanger power, battery size, PTC power, etc. This allowed configurations to be fully explored without the limitations otherwise imposed by pre-designed parts.

2 Modelling

The task of modelling the complex interaction of the vehicle subsystems requires a simulation tool capable of integrating multi-domain subsystems in an acausal way. For example, the heat flux of two interconnected objects must be able to flow in either direction depending on the temperature difference, without needing the model to be manually rearranged. Where there is an action within the system, the reaction of the neighbouring objects and their influence on the action must be represented. The simulation tool should also allow the user to customise components where required, without having to rely on external developers to create new components for us. Dymola and relevant model libraries were used for all the CAE undertaken in this project.

Each part of the system is modelled as an object with the correct physical interface. The acausal nature of the models allows the use of across or flow variables as boundaries. In the thermal domain these would be a temperature boundary condition or heat flow boundary condition for a given component. The same is true for the mechanical, electrical and fluid domains. Inverse and forward dynamic modelling is therefore easily achieved using exactly the same component models in both forward and inverse scenarios.

An automated analysis and manipulation of the system equations optimises the efficiency of the code hence allowing the model to run faster without necessarily relying on the user to improve their code.

2.1 The vehicle model

A whole vehicle model is used as a framework and is based on previous work [1], [2], [3], [4]. The model architecture is extended and appropriate subsystem models are slotted into the vehicle architecture. This type of modelling allows each subsystem to be easily replaced with one of lower or higher fidelity using subsystems compatible with the interface definition (in the case of an electric motor, the mechanical flange and the electrical connections).

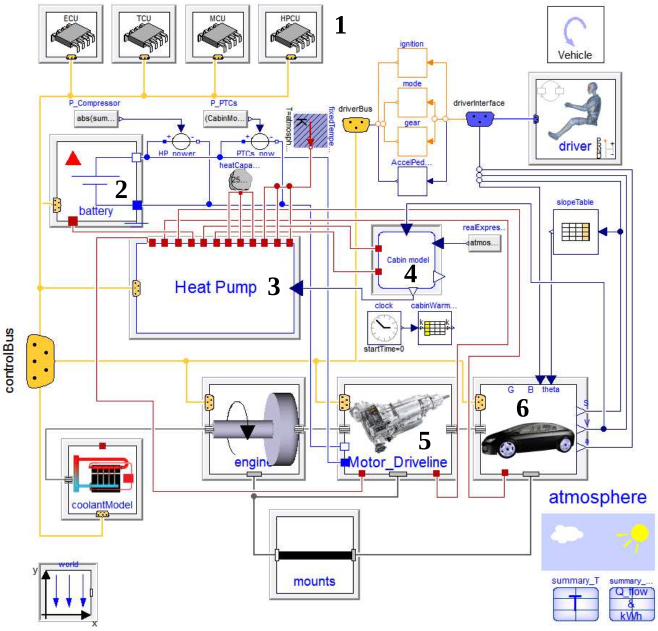

Figure 1: Diagram of overall vehicle model architecture. 1 - Controllers for transmission, electric drives and heat pump system, 2 – BEV battery, 3 – Heat pump model including fluid circuits, 4 - Cabin model, 5 - Transmission model, 6 – Chassis and brakes model.

2.2 The heat pump model

The heat pump model consists of a twin condenser and single evaporator non reversible system.
Coupled to each condenser and evaporator in the heat pump loop is a liquid fluid circuit. The 3 liquid fluid circuits allow heat energy to be exchanged with vehicle subsystems that have been thermally connected to each of the loops. The system model should allow vehicle subsystems to be connected to one of the 3 loops at any point in time or to be thermally isolated when required.

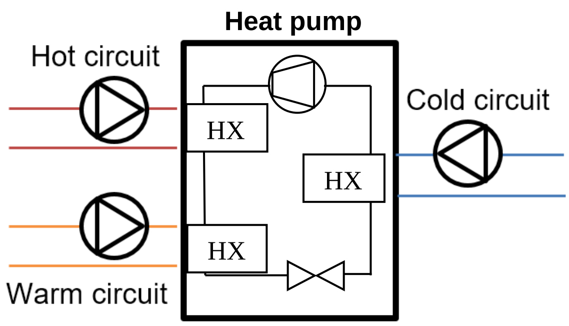

Figure 2: Schematic of the heat pump and liquid fluid circuits.

Each liquid fluid loop (circuit) integrates a pump to allow the fluid to transport heat energy to and from the components coupled to each loop. A target temperature is established for each loop and the heat pump will be controlled to achieve the set-point temperatures which can vary during operation.

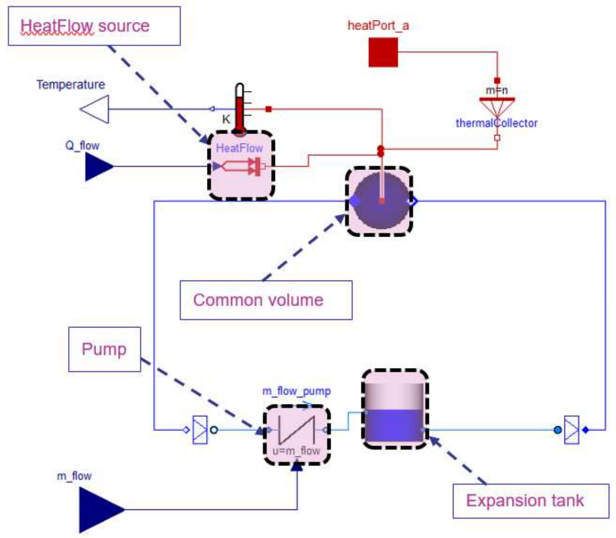

Figure 3: Schematic of the liquid fluid circuit model.

An expansion tank is included within each of the 3 circuits to accommodate the fluid expanding and contracting with fluctuations in temperature (Figure 3). The circuit pipework is lumped within a common volume model to which subsystems can be thermally coupled. Heat exchange between each circuit and the heat pump loop is modelled through heat flow sources and sinks. A target CoP is defined for the heat pump system and can be tuned if required.

Because of the conceptual nature of the heat pump system, the heat pump model has been simplified to be a heat-moving system with sensible limitations in terms of heat transfer power and thermal mass of the components mainly related to sizing of heat exchangers.

In the initial stages, a real heat pump system on a rig had been considered as a candidate for this study. The use of this system was later dismissed as the sizes of the components could cause limitations to the system performance.

2.3 The battery model and electric motor-generator model

The electric motor model is based on a miked empirical and physical modelling approach with heat losses and thermal properties of the materials taken into account. The electric motor performance and efficiency are map based whilst the connections to the electrical network and mechanical components are supported via physical connectors.

Battery demand from motor = requested traction power + motor losses (1)

The battery model is based on an equivalent circuit battery model with heat losses and temperature dependant internal resistance. The battery model also has defined losses in respect of whether it is being depleted or recharged. This level of fidelity is required of the battery to account for performance and efficiency changes across the operating temperatures. Both battery and motor-generator models can be increased in fidelity for model reuse in power electronics matching and battery cooling systems analysis.

2.4 The driveline model

The driveline model is built from mechanical component physical models and accounts for losses within the transmission which are temperature, speed and load dependant.

Transmission losses = f(T, w, tau) (2)

Differentials, including the bearings, are also coupled to the 3 circuits in the heat pump system via physical heat ports.

2.4 The energy storage model

An energy storage device is integrated within the vehicle and allowed to be coupled or isolated to/from any of the 3 liquid fluid circuits of the heat pump. For the purposes of this study, the energy storage device will be a thermal mass of arbitrary technology which can store 2MJ of thermal energy from a fully charged to a fully discharged state.
The energy storage device will be able to be pre-charged. For example: when the vehicle is plugged in we could also be using the mains electricity to charge the thermal energy storage device and use this to help keep the cabin warm in cold climate duty cycles. The same thermal energy storage device could also store excess heat during the duty cycle for use within a subsequent duty cycle.
The thermal energy storage device is modelled as a simple thermal mass where:

Heat capacity = specific heat capacity of material * mass (3)

2.5 The cabin model

A multi zone, multi-occupant cabin model used in previous work has been reduced and integrated into the vehicle model. The reduced cabin model is single zone and retains the warm-up and cool-down characteristics of the detailed cabin model. Given that we are not looking at heat distribution within the cabin, a lumped air volume model is deemed to be sufficient. Once a preferred concept for the heat pump operation strategy has been selected, the models could be increased in detail to verify additional benefits given by localised heating or cooling within the cabin. For controller optimisation purposes, models require to be of low computational expensiveness.

3 Experiments

The vehicle model was simulated over a standard climatic test cycle consisting of 30 minutes at a steady 50km/h followed by a further 30 minutes at 100km/h and a final 30 minutes stationary. The external conditions were set to zero wind speed and an ambient temperature of -5 degC.

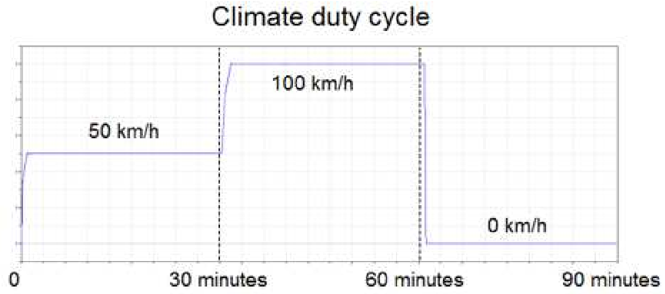

Figure 4: Duty cycle for system testing.

A set of scenarios to be evaluated was drawn up and is listed below.

Key: HB = heat battery, HP = heat pump, HTC = high temperature circuit, LTC= lower temperature circuit, MGU = motor generator unit

1. Baseline model, warming up the components (cabin and electrical battery) with PTCs only.
2. HB pre-charged to 90 degC, the HP is off so the cabin and electrical battery draw the heat directly from the HTC
3. HB pre-charged to 90 degC and initially connected to the HTC loop. When the HB is not able to transfer any more heat to the HTC, it is switched to the Chiller loop. Once the HB is depleted, or when the Chiller coolant loop temperature is lower than ambient temperature, the Chiller coolant loop extracts heat from ambient.
4. HB preconditioned to 90 degC and connected directly to the Chiller coolant loop. Once the Chiller coolant loop temperature is lower than ambient temperature or when the HP is not able to draw any more heat from the HB, the chiller coolant loop starts to draw heat from ambient.
5. HB preconditioned to 90 degC and connected to both HTC and Chiller loops during the time they can draw heat from the HB. Once the Chiller coolant loop temperature is lower than the ambient temperature or when the HB is disconnected from the HP, ambient becomes the main heat source connected to the Chiller coolant loop.
6. HB discharged to -5 degC and connected to the Chiller loop. When the Chiller coolant loop temperature falls below ambient temperature, the chiller coolant loop is able to extract heat from ambient, thus there would be two main heat sources such as ambient and HB.
7. HB disconnected from the HP, the main heat source is the MGU, which is connected to the HP from the start. The Chiller coolant loop draws heat from ambient once its temperature falls below ambient temperature.
8. HB pre-charged to 90 degC and connected firstly to the HTC loop. When the HB is not able to transfer more heat to the HTC, it is switched to the Chiller coolant loop. Once the HB is completely discharged, or when the Chiller coolant loop temperature is lower than ambient temperature, the Chiller coolant loop extracts heat from ambient. The MGU is chilled by the HP

4 Results

The results of the simulation experiments are shown below. Line 1 shows the total cumulative electrical energy consumed from the start of the duty cycle to the end of each 30 minute section. Lines labeled 2-8 show the cumulative % reduction in electrical energy consumption from the traction battery from the start of the duty cycle to the end of each of the three 30 minute sections.

	Battery Consumption (kWh)		
	30 minutes	60 minutes	90 minutes
1	8.42	21.96	23.27
	Energy consumption reduction from Baseline (%)		
2	-17.35%	-7.70%	-7.35%
3	-20.32%	-10.89%	-11.96%
4	-18.45%	-10.34%	-11.55%
5	-19.04%	-10.51%	-11.68%
6	-13.60%	-8.12%	-9.31%
7	-14.86%	-10.09%	-12.89%
8	-22.05%	-13.00%	-15.51%

Figure 5: Cumulative battery consumption for the baseline (1) and alternative scenarios/configurations savings (2-8) with respect to baseline

The 3 scenarios which yielded the highest reductions in electrical energy consumption were 3, 7 and 8:

3. HB pre-charged to 90 degC and initially connected to the HTC loop. When the HB is not able to transfer any more heat to the HTC, it is switched to the Chiller loop. Once the HB is depleted, or when the Chiller coolant loop temperature is lower than ambient temperature, the Chiller coolant loop extracts heat from ambient.

7. HB disconnected from the HP, the main heat source is the MGU, which is connected to the HP from the start. The Chiller coolant loop draws heat from ambient once its temperature falls below ambient temperature.

8. HB pre-charged to 90 degC and connected firstly to the HTC loop. When the HB is not able to transfer more heat to the HTC, it is switched to the Chiller coolant loop. Once the HB is completely discharged, or when the Chiller coolant loop temperature is lower than ambient temperature, the

Chiller coolant loop extracts heat from ambient. The MGU is chilled by the HP.

Scenarios 3 and 8 make use of the pre-charged heat battery and use the heat battery firstly to directly warm up the HTC until the HB achieves thermal equilibrium with the HTC and then to carry on aiding the warmup of the HTC and LTC through heat absorption from the HB via the chiller loop which is operating at lower temperatures. This absorbed heat is then redistributed to the LTC and HTC via the heat pump system to achieve the target circuit temperatures of 50 degC and 90 degC respectively. Both scenarios 3 and 8 allow the heat pump to extract heat from ambient, provided that the chiller liquid fluid circuit is below ambient temperature. The main difference between scenario 3 and 8 is that 8 also uses the MGU as a heat source by chilling it without significant detriments on machine performance.

The results of scenario 7 are important in determining that a heat battery could be replaced by other thermal masses throughout the vehicle for extracting or storing heat. Limitations might be had for preconditioning but there is no reason as to why preconditioning of these thermal masses (MGU for example) could not be evaluated. Scenario 7 assumes no preconditioning of the MGU prior to the start of the duty cycle and allows the heat pump to extract heat from ambient provided that the chiller liquid fluid circuit is below ambient temperature.

Viewing the results from another angle, the energy consumed for moving heat (heat pump system energy consumption) and generating heat (PTCs) is shown below. These are the savings purely for conditioning the cabin and battery subsystems. Even in this case, it is still scenarios 3, 7 and 8 which yield the highest reductions in electrical energy used from the BEV battery.

	Energy used for moving and generating heat (kWh)		
	30 minutes	60 minutes	90 minutes
1	5.82	7.59	8.56
	Energy reduction from Baseline (%)		
2	-25.11%	-22.27%	-19.97%
3	-29.41%	-31.50%	-32.49%
4	-26.71%	-29.90%	-31.39%
5	-27.55%	-30.40%	-31.75%
6	-19.68%	-23.47%	-25.30%
7	-21.51%	-29.18%	-35.02%
8	-31.91%	-37.59%	-42.14%

Figure 6: Cumulative battery consumption for transferring/generating heat for the baseline (1) and alternative scenarios/configurations savings (2-8) with respect to baseline

Further investigations were carried out for studying the effect of different cabin configurations such as:

- Total air recirculation within the cabin.
- Partial air recirculation within the cabin (from 100% to 60% after 2 minutes)
- Installation of a cabin exhaust energy recovery system.

The potential electrical consumption benefits of increasing the maximum power of the chiller were also investigated.

All these studies were based on scenario 8 which yielded the best results so far and is nused as the new baseline the table below:

	Energy used for transferring and generating heat (kWh)		
	30 minutes	60 minutes	90 minutes
Scenario 8: HB charged to 90 degC and connected to HTC loop, then switched to Chiller loop and MGU connected to the Chiller loop (New baseline)	3.96	4.74	4.96
	Energy reduction from Baseline (%)		
Increasing chiller power from 10 to 15 kW	-0.05%	-0.13%	-0.56%
Cabin 100% recirc	-9.15%	-9.39%	-8.93%
Cabin recirc from 100% to 60% after 2 min	-6.65%	-7.06%	-7.48%
Cabin exhaust recovery system at 60%	-4.63%	-5.48%	-5.76%

Figure 7: Cumulative battery consumption for transferring/generating heat for the baseline (Scenario 8) and 4 alternative scenarios/configurations savings with respect to baseline.

Little gain with respect to the baseline is seen increasing the chiller power (0.56%). Limitations in the sizing of other components wihtin the loops could mean that the extra capacity of the chiller cannot be exploited.
The biggest gains are given by increasing cabin air recirculation and using cabin air exhaust heat recovery (5.76-8.93%).

Overall, the results appear to display sufficient benefits to warrant building a prototype system, the specification of which would be developed using the heat transfer requirements from this work to achieve the presented benefits.

References

[1] Gravelle, Robinson & Picarelli. *A Multi-Domain Thermo-Fluid Approach to Optimizing HVAC System.* IMA conference 2014.

[2] Gravelle, Robinson & Picarelli. *Modeling the Effects of Energy Efficient Glazing on Cabin Thermal Energy & Vehicle Efficiency*. Modelica Conference 2015.

[3] Gravelle, Robinson & Picarelli. *Implementation of energy efficient cabin technologies to improve overall vehicle efficiency*. Cenex LCV 2015, Millbrook.

[4] Dempsey, Gillot & Picarelli. *Predicting the Effect of Gearbox Preconditioning on Vehicle Efficiency*. Modelica Conference 2015.